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COMPARATIVE ANALYSIS OF ALTERNATING-PHASE AND COMBINED RF FOCUSING ON THE EXAMPLE OF THE He+ LINEAR ACCELERATOR

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Considered are the peculiarities of focusing by RF field on the example of a helium ion linac with the output energy of 4 MeV of two types: first is the active accelerator based on the modified alternating-phase focusing (MAPF) and second is a proposed accelerator with the combined RF focusing (CRFF) technique used. By means of computer simulation, it is shown that the calculated parameters of the CRFF-based structure offer advantages over the similar parameters of the MAPF-based accelerator. For instance, at low injection current (less than 5 mA) about 60% of charged particles are captured into acceleration process in the CRFF-based structure, while for the MAPF-based one the number is about 42%; the maximum current of accelerated helium ions is 49 and 12 mA, respectively. Owing to the investigations conducted, the conclusion about the prospects of the usage of the CRFF in the future modernization of the helium ion accelerator is presented.

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INTRODUCTION

It is possible to achieve steady acceleration of a bunch of charged particles in an ion linac even without the use of external focusing elements due to the usage of the accelerating RF field itself of the special form. This problem is especially relevant for the ion linacs operating at the low- and medium-energy range, when focusing by magnetic lenses is ineffective due to the low particle velocity and difficult to implement because of short accelerating gaps.

While designing an ion linac operating at low energy, it is important to develop an accelerating structure that accelerates charged particles from low injection energy and features maximum capture efficiency. Nowadays, RFQ [1] structures are used as such accelerating devices. But such structures show certain disadvantages, namely, the low acceleration rate and the complexity of their manufacture. The helium ion linac put into service at NSC KIPT uses the accelerating structures based on the modified alternating phase focusing (MAPF) [2] method. The MAPF-based structure is simple in design, allows particle acceleration from low injection energy, offers the high acceleration rate, however, is inferior in terms of the capture efficiency to the RFQ-based one.

This paper objective is to show that using the combined RF focusing [3] it is possible to significantly improve the output parameters of a charged particle beam without extending the accelerating structure length.

1. PECULIARITIES OF CHARGED PARTICLE BEAM FOCUSING IN A LINAC BY THE ACCELERATING RF FIELD

Let us consider possible methods for radial-phase stability of motion of a charged particle bunch in the high-frequency accelerating and focusing fields in the ion linac.

The motion equation of a charge in the absence of external focusing is

$$\frac{d^2\mathbf{r}}{dt^2} = \frac{1}{m_0\gamma}\mathbf{F}_\omega. \tag{1}$$

Here m_0 is the particle mass, $\gamma = 1/\sqrt{1-\beta^2}$ is Lorentz factor, $\beta = \upsilon / c$ is the relative particle velocity, $\mathbf{F}_\omega$ stands for the force acting on the particle from the RF field.

Let us restrict ourselves to the non-relativistic case and project the Eq. (1) onto the coordinate axis. For certainty, we will consider the particle motion in the standing wave field in a structure with transit tubes. In Cartesian coordinates for a particle with a charge e we get the following set of equations:

$$\begin{aligned} \frac{d^2x}{d^2t} &= \frac{e}{m_0}E_x(x,y,z,t); \\ \frac{d^2y}{d^2t} &= \frac{e}{m_0}E_y(x,y,z,t); \\ \frac{d^2z}{d^2t} &= \frac{e}{m_0}E_z(z,t). \end{aligned} \tag{2}$$

In Eqs. (2) we have neglected the Coulomb forces of particle interaction and the dependence of the longitudinal field component on the transverse coordinates. The second assumption is well satisfied if the channel aperture radius is small compared to the value $\beta\lambda$ (λ is the operating wavelength).

Let us consider the particle motion in a coordinate system which is rigidly bounded with an equilibrium (synchronous) particle. The synchronous particle is the particle that passes though each period of the accelerating structure in a given phase. In turn, the period length must be such that the phase has the calculated value [4]. The equation of the synchronous particle longitudinal motion has the form

$$\frac{d^2z_s}{d^2t} = \frac{e}{m_0}E_z(z_s,t). \tag{3}$$

Having subtracted Eq.(3) from Eq. (2) for the longitudinal component, we have

$$\frac{d(z-z_s)}{dt^2} = \frac{e}{m}\left[E_z(z,t) - E_z(z_s,t)\right]. \tag{4}$$

For asynchronous particles we introduce a dynamical variable

$$q = z(t) - z_s(t). \quad (5)$$

We assume for small longitudinal oscillations

$$E_z(z) - E_z(z_s) = \left.\frac{\partial E_z}{\partial z}\right|_{z=z_s} \cdot q. \quad (6)$$

Then Eq. (4) takes the form

$$\frac{d^2 q}{dt^2} = \frac{e}{m_0}\frac{\partial E_z}{\partial z} q. \quad (7)$$

Because the beam density is assumed to be negligibly small, the electric field in the area of beam interaction with the RF field must obey the equation

$$\mathrm{div}\mathbf{E} = \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} = 0. \quad (8)$$

It is assumed for small oscillations that

$$\begin{gathered} \frac{\partial E_x}{\partial x} \simeq \frac{E_x}{x}; \quad \frac{\partial E_y}{\partial y} \simeq \frac{E_y}{y}; \\ \left.\frac{\partial E_z}{\partial z}\right|_{z=z_s} = \frac{\partial E_z}{\partial q} \simeq \frac{E_z}{q}. \end{gathered} \quad (9)$$

Then, considering Eqs. (7), (8), and (9), we obtain the following equations

$$\begin{gathered} \frac{d^2 x}{dt^2} = \frac{e}{m_0}E_x = -\frac{e}{m_0}\left(\frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z}\right)x; \\ \frac{d^2 y}{dt^2} = \frac{e}{m_0}E_y = -\frac{e}{m_0}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_z}{\partial z}\right)y; \\ \frac{d^2 q}{dt^2} = \frac{e}{m_0}E_z = -\frac{e}{m_0}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y}\right)q. \end{gathered} \quad (10)$$

Let us introduce the notations

$$\begin{gathered} \Omega_x^2 = \frac{e}{m_0}\left(\frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z}\right); \\ \Omega_y^2 = \frac{e}{m_0}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_z}{\partial z}\right); \\ \Omega_q^2 = \frac{e}{m_0}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y}\right). \end{gathered} \quad (11)$$

Then, taking into account Eqs. (11), we rewrite Eqs. (10) as

$$\begin{gathered} \ddot{x} + \Omega_x^2 x = 0; \\ \ddot{y} + \Omega_y^2 y = 0; \\ \ddot{q} + \Omega_q^2 q = 0. \end{gathered} \quad (12)$$

Let us consider Eqs. (12) in terms of the possibility of steady particle acceleration. Note that in electrostatic fields or at each definite moment of time the steady motion of charged particles is possible only for the trivial case $\Omega_x^2 = \Omega_y^2 = \Omega_q^2 = 0$ since Eq.(8) implies the equality [5]

$$\Omega_x^2(t) + \Omega_y^2(t) + \Omega_q^2(t) = 0. \quad (13)$$

In this case, the steady localization of the accelerated particles can be achieved by applying the principle of alternating-sign or strong focusing, using the RF field itself. The brief history of RF focusing is presented in Fig. 1. At present, two variations of focusing by RF field are used in practice, namely, alternating-phase and RFQ.

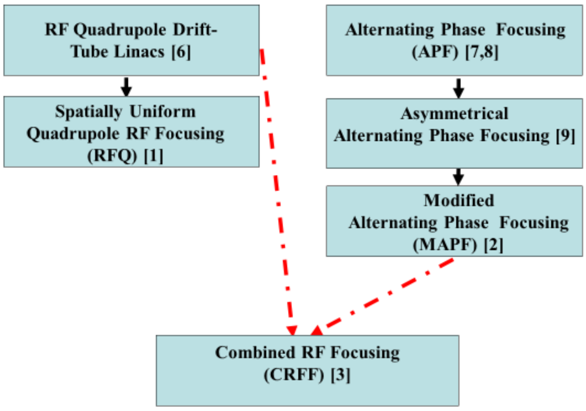

Fig. 1. Main versions of RF focusing: brief history

Fig. 2 presents NSC KIPT's active linacs based on RFQ and MAPF focusing as well as a model of the CRFF-based accelerating structure under development.

a *b* *c*

Fig. 2. Accelerators of the NSC KIPT: a – RFQ-based proton linac URAL-5 [10], output energy 5 MeV; b – MAPF-based helium ion linac, output energy 4 MeV [11]; c – CRFF-based prestripping section (model) of the MILAC accelerator, output energy 1 MeV/nucleon (mass number-to-charge ration is $A/q \leq 20$) [12]

2. TECHNIQUES FOR ION FOCUSING BY THE RF FIELD

2.1. RFQ

In the case of ion focusing using the RFQ technique, the particle phase stability is provided by the autophasing principle, while in the transverse direction the particles are subjected to defocusing forces of the RF field. The radial stability of particles can be ensured by abandoning the axial symmetry of the RF field and periodically alternating the sign of the coefficients Ω_x^2 and Ω_y^2 along the accelerating channel. For instance, let the travel time over the accelerating period be T, then

$$\Omega_x^2(t) > 0, \quad \Omega_x^2(t) > 0, \quad \Omega_y^2(t) < 0; \quad 0 \le t \le T/2;$$
$$\Omega_x^2(t) > 0, \quad \Omega_x^2(t) < 0, \quad \Omega_y^2(t) > 0; \quad T/2 \le t \le T.$$

In practice, the realization of the RF field with a quadrupole component can be achieved either by introduction of additional electrodes into the accelerating gap or by using electrodes of extended quadrupole shape as in an RFQ structure. Such a structure makes it possible to focus all the beam particles regardless of their velocity or phase. The accelerating component is provided by the longitudinal electrode modulation. In the low-energy range (2…3 MeV), RFQ accelerators are currently used. They do not require a high-power injector and provide almost 100% capture, acceleration and focusing of charged-particle beams at a high value of limiting current. Despite its simplicity and good compatibility with superconducting structures, quadrupole focusing by the RF field in high-current linacs operating in the medium-energy range has not became widespread. The only active linear accelerator running without special external electromagnetic focusing devices is the 30 MeV proton injector. This machine dubbed URAL-30 was put into service at the Institute of High-Energy Physics (Russia) in 1981. The advantage of this linac is its simplicity in design, operational reliability, and low cost. Among its disadvantages is rather low accelerating rate (the output energy of 30 MeV over the channel of 26.5 m in length). To focus and accelerate the beam in the main accelerator part a principle of 'double-gap' has been implemented [10]. According to the 'double-gap' concept, to ensure radial and phase stability, an additional electrode is introduced into each accelerating gap dividing it into two parts: axisymmetric and quadrupole. In the former part, particles are accelerated and phased. In the latter, due to the introduction of the additional electrodes, a quadrupole component of the accelerating field is generated. Periodic alternation of the RF quadrupole orientation in the neighboring accelerating periods ensures the radial stability of particle motion.

2.2. ALTERNATING-PHASE FOCUSING

Alternating-phase focusing is a type of RF focusing in an axially symmetric accelerating field. In this case,

$$\Omega_x^2(t) = \Omega_y^2(t) = -\frac{1}{2}\Omega_q^2(t). \qquad (14)$$

Then, Eq. (10) can be rewritten as

$$\begin{aligned} &\ddot{r} - \frac{1}{2}\Omega_q^2(t) r = 0; \\ &\ddot{q} + \Omega_q^2(t) q = 0. \end{aligned} \qquad (15)$$

As this takes place, Eqs. (15) must have the area of joint stability over the focusing period.

To ensure both longitudinal and transverse stability of the beam motion is possible due to the sign alternation of Ω_q^2 coefficient along the accelerating system. At first, to provide radial and phase stability it has been suggested to periodically change the sign of the phase of the synchronous particle from gap to gap [7, 8]. In this case, the longitudinal and transverse forces acting on the particle are sign-alternating. Under certain conditions it is possible to provide simultaneous longitudinal and phase stability of the particle motion during the acceleration process in such a structure. However, as it turned out, in this case the joint area of longitudinal and transverse motion stability exists only for a very small range of accelerator parameters. Besides, the phase length of the separatrix turns out to be extremely small and amounts to only a few degrees. As, from the practical point of view, this focusing method is significantly inferior to strong focusing by magnetic quadrupole lenses, APF has been only of theoretical interest for a long time.

Later, the solutions to this problem were found that made it possible to expand the beam capture area into steady acceleration suitable for practical applications. In Ref. [9] it was proposed to introduce an asymmetry into the structure of the focusing period by periodically changing not only the synchronous particle phase sign along the accelerating&focusing channel but also at least one accelerator parameter: the absolute value of the synchronous phase and/or the accelerating field amplitude. The first accelerator based on the asymmetric alternating-phase focusing was commissioned at the MRTI of USSR Academy of Sciences in 1972. Later, at the KIPT of the Academy of Sciences of the Ukrainian SSR (now NSC KIPT), a modified method for APF was proposed – modified alternating phase focusing [2] which made it possible not only to expand significantly the area of particle capture into the acceleration mode but also to increase the accelerated current. The idea behind MAPF is to increase the number of accelerating gaps over the focusing period that allows expanding the capabilities of the accelerating&focusing channels for various energy ranges, types of accelerated particles, magnitudes of accelerated current, etc. The first accelerator of this type, a small-sized linear deuteron accelerator based on MAPF put into service at the KIPT, confirmed the effectiveness of this method [13]. Later on, several more accelerators of this type were developed and created.

3. A PROMISING FOCUSING METHOD BY THE ACCELERATING FIELD – COMBINED RF FOCUSING (CRFF). COMPARATIVE ANALYSIS OF APF AND CRFF

Let us consider advantages, disadvantages and ways of improvement on MAPF using the 4 MeV helium ion linac as an example (Fig. 3) [11].

MAPF-based structures feature constructive simplicity and allow particle acceleration from low injection energies. To increase the particle capture angle into the acceleration mode, a growing field is used at the grouping section of the accelerating gaps in this type of accelerator. The entire accelerating&focusing channel consists of separate focusing periods each of which houses a certain number of gaps with negative and positive synchronous phases. The synchronous phase value in the accelerating gaps is chosen in such a way that for a given accelerating field distribution over the gaps, both the longitudinal and transverse beam stability is ensured simultaneously at the maximum accelerating rate (Table 1).

a *b*

Fig. 3. Accelerating structure of helium ion linac with output energy 4 MeV: inside view (a); accelerating&focusing channel with tuning elements (b)

Table 1

Structure of the accelerating&focusing channel of the helium ion linac

Period number	Synchronous phase, degrees	Electric field, kV/cm
1	-90; 75; 60; 0; -60	27.5…37.5
2	-90; 75; 60; 0; -50	40…50
3	-85; 75; 60; 0; -65	52.5…62.5
4	-70; 75; 60; 0; -60	65…75
5	-90; 75; 60; 40; 0; -60	75
6	-60	32.5

In the MAPF-based accelerators longitudinal and transverse focusing is provided by the same accelerating field. As this takes place, an increase in rigidity of longitudinal focusing leads to the eminent weakening of the transverse one. This results in a limitation of the accelerated current compared to the accelerators using the autofocusing principle and external focusing devices. To solve this problem, it was proposed to use CRFF method, in which the MAPF-based accelerating&focusing period is supplemented with a quadrupole RF focusing technique to increase longitudinal focusing rigidity (see Fig. 4).

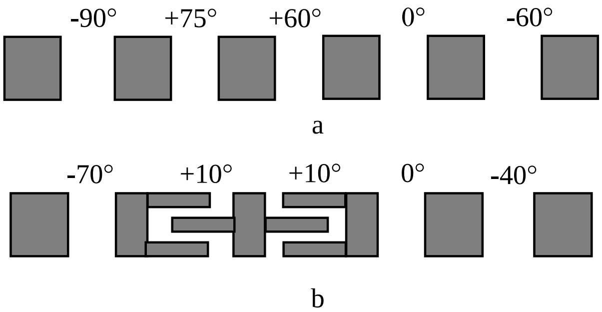

Fig. 4. Layout of the first accelerating&focusing period and synchronous phase distribution: MAPF (a); CRFF (b)

Table 2 presents the main parameters of these two focusing methods. Fig. 5 shows the dependence of the helium ion current at the accelerator exit on the injection current.

As expected, the calculated parameters of the CRFF-based accelerator exceed the similar ones of the MAPF-based structure. Thus, at low injection current (less than 5 mA) about 60% of charged particles are captured into the acceleration mode in the CRFF-based structure, while for the MAPF-based one the number is about 42%; the maximum current of accelerated helium ions is 49 and 12 mA, respectively. The rise in the reduced rms emittance for the CRFF-based structure is 2 times less than for the MAPF-based one at the current of 12 mA.

Table 2

Parameters for two helium ion linacs

Parameter	MAPF-based	CRFF-based
Operating frequency, MHz	47.2	47.2
Injection energy, keV/nucleon	30	30
Output energy, MeV/nucleon	1	1
Channel length, cm	237.7	222
Number of gaps	32	26
Channel radius, cm	0.75…1.5	0.75…1.2
Maximum current at the accelerator exit, mA	12	49
Coefficient of beam capture at low injection current, %	40	60
Input beam emittance, mm·mrad $\varepsilon_{n,x}(rms)$, $\varepsilon_{n,y}(rms)$	0.150	0.150
Output beam emittance at 12 mA current, mm·mrad $\varepsilon_{n,x}(rms)$ $\varepsilon_{n,y}(rms)$	0.616 0.581	0.289 0.268

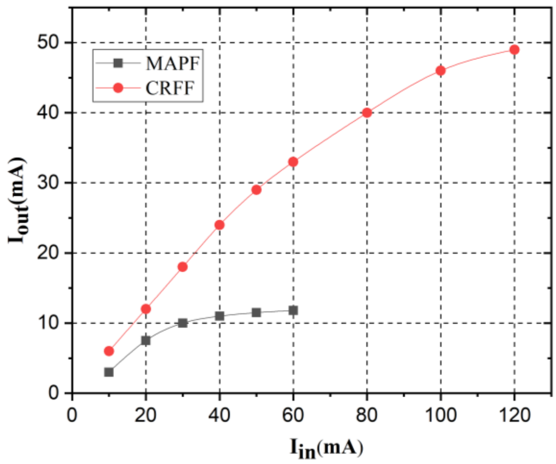

Fig. 5. Helium ion current dependencies on injection current at the accelerating structure exit

CONCLUSIONS

Owing to the investigations conducted, the usage of the CRFF technique for further modernization of the helium ion accelerator looks promising. At the same time, the entire exiting infrastructure of the linac remains the same; only the accelerating structure is to be replaced. It also should be noted that the elements of the CRFF-based structure, such as the gaps with quadrupole symmetry of the transverse RF field, the global and local elements for adjusting the RF field amplitude have shown their efficiency when used in the operating accelerators at the NSC KIPT.

The considered CRFF technique is of a general nature and can be used to accelerate particles with various mass-number-to-charge ratio (*A/q*) in the small-sized high-current linear accelerators for solving fundamental and applied problems.

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ПОРІВНЯЛЬНИЙ АНАЛІЗ ЗМІННО-ФАЗОВОГО ТА КОМБІНОВАНОГО ВЧ-ФОКУСУВАННЯ НА ПРИКЛАДІ ЛІНІЙНОГО ПРИСКОРЮВАЧА ІОНІВ ГЕЛІЮ

С.С. Тішкін

Розглянуто особливості фокусування ВЧ-полем на прикладі двох варіантів лінійного прискорювача іонів гелію з вихідною енергією 4 МеВ: діючий прискорювач з модифікованим змінно-фазовим фокусуванням (МЗФФ) та запропонований прискорювач з комбінованим ВЧ-фокусуванням (КВЧФ). За допомогою математичного (комп'ютерного) моделювання показано, що розрахункові параметри прискорювача з КВЧФ мають переваги перед прискорювачем з МЗФФ. Так, захоплення частинок у режим прискорення при малому струмі інжекції (<5 мА) становить 60% при КВЧФ та 42% при МЗФФ; максимальний струм прискорених іонів гелію 49 та 12 мА відповідно. Проведені дослідження дозволяють зробити висновок про перспективність використання КВЧФ при подальшій модернізації прискорювача іонів гелію.